Movement and diet in early Irish prehistory

Movement and diet in early Irish prehistory: first evidence from multi-isotope analysis

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This paper presents the results of a pilot study utilising a multi-isotope approach to studying population mobility and diet in early prehistoric Ireland. In particular it combines the use of strontium, carbon and nitrogen analysis as well as AMS radiocarbon dating on human remains from later Mesolithic and early to middle Neolithic contexts. The results demonstrate significant variation in the strontium signatures, suggesting a degree of mobility among both the Mesolithic and Neolithic individuals. They also highlight, however, the importance of providing a model for biologically available strontium across the Irish landscape so that a more refined interpretation of datasets like this is possible. The results from stable isotope analysis demonstrate that all Neolithic individuals did subsist on a heavily terrestrially based diet. Although this was also the case for the Mesolithic individuals, one showed possible indicators for the consumption of freshwater fish.

INTRODUCTION

Despite its relatively small-scale nature, this study of the remains of ten individuals represents one of the first projects providing a strategic approach to multi-isotope analysis of Irish early prehistoric remains. For the first time it combines strontium, carbon and nitrogen analysis with radiocarbon dating on Mesolithic and early Neolithic human remains to address questions relating to their lifetime movements, mobility and diet.

The study began as a Heritage Council research grant-aided project with the aim of addressing the question of the role of migration in bringing about the introduction of agriculture to Ireland. As has been demonstrated elsewhere (e.g. Cooney *et al.* 2011; Whitehouse *et al.* 2013), however, the Mesolithic–Neolithic transition is extremely difficult to identify chronologically. Consequently the project had to start by analysing (what were believed to be) some of the known latest Mesolithic and earliest Neolithic human remains from the country. The research strategy was quite simple: identify the latest available previously dated Mesolithic and the earliest available previously dated Neolithic human remains from Ireland and conduct multi-isotope analysis (including $^{87}Sr/^{86}Sr$, $\delta^{13}C$ and $\delta^{15}N$) on them. Moreover, with one exception (Annagh, burial 1) there was no reliable anatomical association between the previously dated samples and the bones sampled for this study. Therefore all but this one sample had to be re-dated to provide a secure chronological footing for the project.

Although isotope—and, in particular, strontium—analysis is still relatively new to Irish archaeological research, in recent years the number of isotope studies has begun to increase considerably. They have included research on strontium in later prehistory—such as at Knowth (Cahill Wilson *et al.* 2012) and the Hill of Tara (Sheridan *et al.* 2013)—and the early medieval period (Cahill Wilson, forthcoming), as well as Viking Dublin (Knudson *et al.* 2012). In addition, a number of projects have produced isotope data (carbon and nitrogen) pertaining to dietary habits, for example from Neolithic court tombs (Schulting *et al.* 2012) and during the Irish Famine (Beaumont *et al.* 2012). There are also two recent projects involving isotope analysis on Neolithic burials from County Clare: Parknabinnia (Snoeck *et al.*, forthcoming) and Poulnabrone portal tomb (Lynch 2014). The present study can be positioned alongside this emerging interest in the benefit of isotope research to help answer archaeological questions.

OBJECTIVES AND METHODS

The central objective of this programme is to assess the merits of employing a multi-isotope analysis methodology to study daily life and key changes in Irish early prehistory through studying human remains. This includes the analysis of strontium isotopes to provide evidence for potential population movements and mobility, and carbon and nitrogen isotopes to gain insights into changes in diet, especially from the Mesolithic to the Neolithic period.

Strontium in human remains

Several recent publications have discussed in detail the methodological and theoretical aspects of using strontium isotope analysis to track population movements (Bentley 2006; Montgomery 2010; Price *et al*. 2001) and thus only a brief summary is required here. The approach 'rests on the principle that rocks of different types and ages have characteristic strontium isotope ratios (conventionally $^{87}Sr/^{86}Sr$) and these ratios do not alter (fractionate) in any measurable way as the element is transferred from the source rocks through the biosphere' (Montgomery 2010, 326–7). Consequently, the strontium isotope ratio measured in human skeletal remains can be related to the geology of the region where the individuals sourced the majority of their food and drinking water. An ever-increasing number of studies have demonstrated, however, that the relationship between the strontium ratio in human skeletal tissue and that in the bedrock geology is not a straightforward one (Bentley 2006; Evans *et al*. 2010). Essentially, the strontium ratio in the biosphere, which ultimately enters the human and animal metabolism, can be different from that of the underlying geology, as the various minerals making up the bedrock may weather at different rates. There are also 'additional, non-geologic sources of strontium in the biosphere' and ideally one should 'match the isotopic signatures from an individual to the biologically-available signature at a suspected location of origin' rather than relying purely on geology (Bentley 2006, 136).

The second key consideration in strontium analysis relates to the tissue sampled. Mammal bone is constantly turned over during life, meaning that depending on the type of bone all the elements within it (including strontium) are recycled over a number of years. In contrast to this, enamel of the permanent dentition is formed in infancy (starting *in utero*) and childhood; once completed, by about fourteen years of age, it does not alter any further (White and Folkens 2005, 127–8). Therefore dental enamel reflects the $^{87}Sr/^{86}Sr$ ratio of the region where the individual grew up and the key geographic sources of his diet. In very simple terms, if this ratio differs from that of the local biosphere where the remains have been deposited it suggests that the individual must have moved there during his lifetime (Bentley *et al*. 2004; Bickle and Hofmann 2007, 1029; Trickett *et al*. 2002). In addition to this, dental enamel is also extremely durable and much less liable to diagenetic alteration than other skeletal tissues, such as bone and dentine (Budd *et al*. 2000).

A significant number of publications have also been produced discussing the use of carbon and nitrogen analysis for dietary reconstruction (Beaumont *et al*. 2012; Cadwallader *et al*. 2012; Kuhnle *et al*. 2012; Montgomery *et al*. 2013; Richards and Schulting 2006; Schulting *et al*. 2012). Put simply, the ratio of carbon-12 to carbon-13 (expressed as $\delta^{13}C$) in human and animal organisms relates to the key sources of dietary protein. If the diet is entirely based on terrestrial food sources from temperate Europe, with no input of C_4 plants (Cadwallader *et al*. 2012), we can expect a bone collagen $\delta^{13}C$ ratio below −18‰, and in northern C_3 environments even as low as −22‰. If there is significant marine input into the diet, however, it becomes more enriched in ^{13}C, meaning that the values are higher, up to −12‰, for a strongly marine-based diet (Kuhnle *et al*. 2012; Schulting and Richards 2000).

Nitrogen isotopes provide a measure of human diet that is independent of carbon. The nitrogen value in organisms increases the higher they are positioned up the food-chain (i.e. with increasing trophic level). In fact, $\delta^{13}C$ ratios also increase with rising trophic levels but not to the same extent as $\delta^{15}N$. As the food-chains in a marine setting tend to be much longer than on land, people subsisting largely on a marine diet will have significantly elevated $\delta^{15}N$ values (Kuhnle *et al*. 2012). Therefore, in combination, carbon and nitrogen analysis can provide a good indication of marine input into the diet.

SAMPLES AND ANALYSIS

As already alluded to above, samples were selected based on existing dating evidence that put them close to the 39th century BC, the most probable date around which the transition to agriculture in Ireland currently appears to have occurred (Cooney *et al*. 2011; Whitehouse *et al*. 2013). They were taken from ten individuals originating from six sites around Ireland (Table 1; Fig. 1). They comprised ten samples of dental enamel for strontium isotope analysis, and eight samples of bone and one of dental collagen for AMS ^{14}C dating, carbon and nitrogen analysis. All samples were prepared and taken by the project osteologist, Linda Fibiger, except the tooth from Ballynaclogh, which was sampled by Denise Keating. As the human remains in question represent some of the oldest—and thus arguably most important—remains known from Ireland, best conservation practice was one of the key considerations for the sampling stage of the project. This was pursued by minimising the destructive impact the sampling had on the remains. For the dental enamel samples a small piece of enamel was removed from the lingual side of the molar (Mays *et al*. 2013). This meant that even if the remains were to be put on public display in a museum or collection there would be no

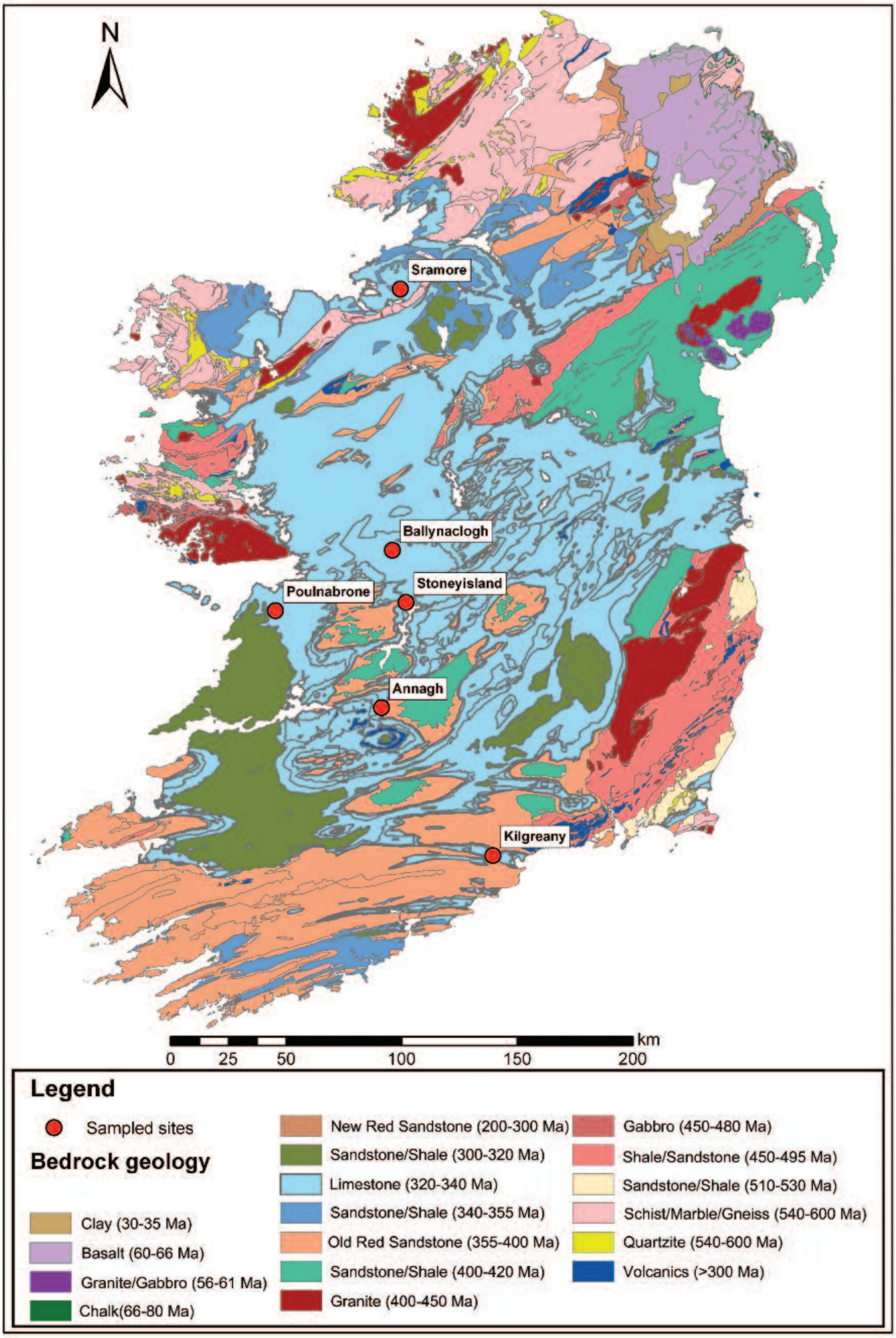

Fig. 1—Geological map of Ireland (based on the GSI 1:500,000 bedrock map), showing the find locations of the samples discussed.

Table 1—Summarising all the results relating to the samples and their analysis.

ID	Site	County	Details	Age	Sex	Lab no.	Date BP	±	Date cal. BC	$^{87}Sr/^{86}Sr$	s.d.	$\delta^{13}C$	%C	$\delta^{15}N$	%N	C:N
AGH01	Annagh	Limerick	Burial III	Adult >20 years	Male	GrA-1707*	4810	60	3706–3379	0.712042	0.0008	N/A	N/A	N/A	N/A	N/A
AGH02	Annagh	Limerick	Burial IV/V	Adult >30 years	Indet.	UB-15766	4682	29	3624 – 3370	0.709419	0.0007	-20.9	15.35	9.45	5.5	3.26
BNC01	Ballynaclogh	Galway	tooth	Adult	Indet.	N/A	Failed	N/A	N/A	0.708900	0.0006	N/A	N/A	N/A	N/A	N/A
KGY01	Kilgreany	Waterford	Burial 2 [B]	Adult >30 years	Male	UB-15767	4393	45	3321 – 3272	0.710682	0.0008	-21.9	8.45	9.73	2.85	3.47
PNB01	Poulnabrone	Clare	Burial 1	Adult >20 years	Prob. female	UB-15768	4731	31	3634 – 3551	0.708560	0.0008	-21.5	15.8	9.07	5.75	3.18
PNB02	Poulnabrone	Clare	Burial 2	Adult >20 years	Poss. male	UB-15769	4728	28	3633 – 3554	0.708907	0.0007	-19.6	23.8	8.69	8.45	3.28
PNB03	Poulnabrone	Clare	Burial 3	Adult >20 years	Prob. male	UB-15770	4894	28	3710 – 3639	0.709026	0.0007	-22.3	21.8	8.04	7.85	3.23
PNB04	Poulnabrone	Clare	Burial 4	Juvenile 1.5–2 years	N/A	UB-15771	4508	32	3352 – 3261	0.708839	0.0007	-21.8	22.65	10.16	8.05	3.27
SRA01	Sramore	Leitrim	Mandible	Adult >30 years	Poss. male	UB-15772	5227	36	4227 – 3963	0.708633	0.0008	-20.4	25.8	8.52	9.4	3.22
STI01	Stoneyisland	Galway	Bog find	> Adult >20 years	Male	UB-15765	6168	31	5215 – 5027	0.708486	0.0007	-21.4	26.7	11.82	8.75	3.55

For greater detail on the locations and remains see Kador 2010.

*AGH01 was dated as part of another project; see Table 2 (source: Dowd 2008).

Table 2—Indication of bio-available strontium from some of the sites, based on plant remains and published results.

ID	Site	County	$^{87}Sr/^{86}Sr$	s.d.
AGH_V	Annagh	Limerick	0.70952	0.00014
BNC_V	Ballynaclogh	Galway	0.70788	0.00010
PNB*	Poulnabrone	Clare	0.70870	N/A
TB_586616 **	Sramore	Leitrim	0.70827	0.00006
TB_586671 **	Sramore	Leitrim	0.70941	0.00011
TB_586677 **	Sramore	Leitrim	0.70936	0.00007
TB_587073 **	Sramore	Leitrim	0.70886	0.00007
TB average**	Sramore	Leitrim	0.70898	0.00008
STI_V	Stoneyisland	Galway	0.70894	0.00013

*Average of samples 101–113 from Ditchfield 2014, 91.

**Samples labelled TB were collected as part of the TELLUS Border project (Geological Survey of Ireland 2014).

apparent damage to the tooth visible from the outside (buccal side). Similarly, we aimed to keep to a minimum the damage caused to skeletal material by taking collagen samples. Where possible, we utilised fragments of bone that had become detached from the cranium/mandible during storage, as long as they were clearly anatomically attributable to the sampled individual. Where this was not possible, a mechanical drill was used to remove collagen powder from the lingual side of the mandible. This meant that the mandible remained largely intact, except for surface damage to the lingual side, and, as with the molars, no damage was visible from the buccal side. Further details on the sampling and curation strategy are outlined in the final Heritage Council project report (Kador 2010).

Each sampled individual was also subjected to a brief osteological examination, to determine age, sex and other characteristics. Age assessment of the human remains was based on observing dental calcification, growth, eruption and wear (Smith 1991; Ubelaker 1989, fig. 71). As most of the individuals (with the exception of the Stoneyisland remains) were represented merely by the cranium and articulated mandible, it was only possible to give broad age ranges for the adult remains. Sex assessment was carried out on adult skeletal remains only, assessing up to fifteen morphological features of the skull (Buikstra and Ubelaker 1994, 19; Herrmann *et al.* 1990). Owing to poor and incomplete preservation it was not possible to ascribe sex confidently to all the remains (Table 1).

AMS radiocarbon dating and stable isotope analysis

Radiocarbon dating as well as carbon and nitrogen analysis were conducted at the ^{14}CHRONO Centre, Queen's University Belfast. For this approximately 0.5g of bone collagen was drilled from the lingual side of the mandibles and submitted to the laboratory. The only exception to this was Ballynaclogh. As this sample was represented by a loose tooth only, the entire tooth was forwarded to the laboratory for dating and stable isotope analysis on the dental collagen after the enamel sample for strontium analysis had been taken. After collagen extraction, $\delta^{13}C$ and $\delta^{15}N$ were measured on a Delta V Isotope Ratio Mass Spectrometer (IRMS), while ^{14}C measurement for dating took place on the Accelerator Mass Spectrometer (AMS) (Reimer *et al.* 2015).

Strontium analysis

For strontium analysis a small sample (*c.* 0.01g) of enamel was removed, generally from the first permanent molar (M1). Analysis of the strontium isotope ratios within these samples was conducted at the Department of Geological Sciences at the University of North Carolina, Chapel Hill. Additionally, a small number of vegetation samples taken from the vicinity of four of the six sites were also analysed for strontium (Table 2). They included four samples from the vicinity of Sramore Cave, collected as part of the TELLUS Border Project (Geological Survey of Ireland 2014). Analysis of these samples was carried out at the Bristol Isotope Group (BIG) laboratory, School of Earth Sciences, University of Bristol (Triantaphyllou *et al.* 2015). For both enamel and plant material strontium was separated from dissolved samples by ion exchange chromatography using Eichrom Sr-Spec resin (Horwitz *et al.* 1992). The tooth enamel samples were analysed in dynamic multi-collector mode with a VG Sector 54 thermal ionisation mass spectrometer (TIMS). Ratios were corrected to an $^{87}Sr/^{86}Sr$ value of 0.710250 for carbonate standard

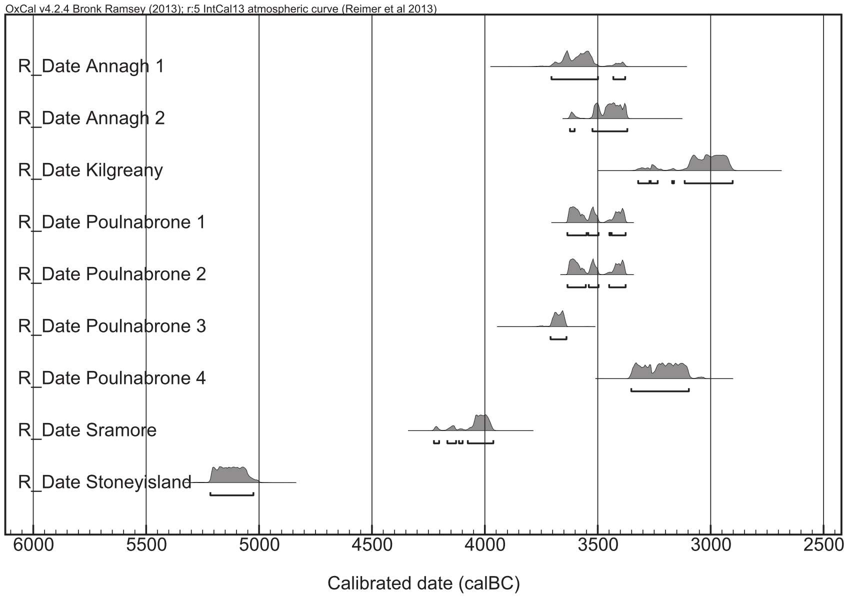

Fig. 2—OxCal radiocarbon correction plot for the sampled remains.

SRM 987 (Slovak and Paytan 2011, 754). Internal precision, as percentage standard error for $^{87}Sr/^{86}Sr$ isotopic ratios, is typically 0.0006 to 0.0009. Sr carbonate standard SRM 987 was analysed 62 times during this study: average $^{87}Sr/^{86}Sr$ ratio = 0.710270 ± 0.000018 (2 standard deviations). The isotope ratios for the plant remains were measured on a Thermo Triton thermal ionisation mass spectrometer (TIMS) and corrected to an $^{87}Sr/^{86}Sr$ value of 0.710248 for carbonate standard SRM 987 (Triantaphyllou *et al.* 2015). Internal precision for $^{87}Sr/^{86}Sr$ isotope ratios is typically ±0.00001.

RESULTS AND DISCUSSION

Radiocarbon dating

With the exception of Ballynaclogh, all nine samples submitted to ^{14}CHRONO for radiocarbon dating had sufficiently intact collagen to provide ^{14}C readings (Table 1; Fig. 2). Four of the eight successful samples returned dates during the first half of the fourth millennium BC (AGH01, PNB01–03) and could thus be characterised as of early Neolithic date (Whitehouse *et al.* 2013). Two samples (KGY01 and PNB04) returned dates in the second half of the fourth millennium, making them middle Neolithic (Cooney 2000; Cooney *et al.* 2011; Whitehouse *et al.* 2013). The remaining two samples have been dated to the later Mesolithic period, one to the late fifth (SRA01) and the other to the late sixth (STI01) millennium BC (Costa *et al.* 2005; Woodman 2012). The latter date suggests that the human remains from Stoneyisland are significantly older than the previously obtained dates had indicated (Hedges *et al.* 1993; Meiklejohn and Woodman 2012, 32–3; Table 3). The original dates obtained by Brindley and Lanting were published in a section titled 'Experimental Bone Chemistry' and related to 'experimental work involving the use of the enzyme collegenase to digest ancient collagen' (Hedges *et al.* 1993, 323). The dates thus derived are not directly on the ancient collagen samples but on peptide mixtures resulting from this digestion. Thus it is possible that this experimental process could have resulted in the dates being too young. Interestingly, Hedges *et al.* (1993, 323) published a date of 6200±80 BP measured on the ion-exchanged gelatine (OxA-2758), together with the other Stoneyisland dates, which calibrates as 5325–4942 cal. BC (at 95.4% certainty), hence relatively close to our date from Stoneyisland (Table 1). Alternatively, if, as is possibly indicated by the stable isotope evidence (see below), the individual from Stoneyisland did consume a significant amount of freshwater fish, there could be a freshwater reservoir effect, which would make the date appear anomalously old. It is unclear, however, whether this effect could be great enough to account for the discrepancy of over a millennium between the old and new dates (Philippsen 2013). Our new date for Sramore corroborates the final fifth- or early fourth-millennium BC date on a femur from the same site obtained recently for a different project (Dowd 2008). The chronological proximity of the two dates suggests that the mandible and the femur may have belonged to the same individual. On balance they should probably be attributed to the final Mesolithic rather than to the earliest Neolithic period, but this cannot be stated with absolute certainty (cf. Cooney *et al.* 2011; Sheridan 2010; Whitehouse *et al.* 2013). The early Neolithic dates from both Annagh and Poulnabrone are in keeping

Table 3—Radiocarbon dates previously obtained from the sites investigated.

Site	County	Lab no.	Date BP	±	Date cal. BC	Sample
Annagh burial 1	Limerick	GrA-1703	4670	70	3639–3138	Right scapula
Annagh burial 2	Limerick	GrA-1704	4780	60	3660–3375	Right scapula
Annagh burial 3	Limerick	GrA-1707	4810	60	3706–3379	Right scapula
Annagh burial 4	Limerick	GrA-1708	4640	60	3633–3123	Right scapula
Annagh burial 4	Limerick	GrA-1709	4840	60	3767–3384	Right scapula
Kilgreany burial A	Waterford	BM-135	4660	75	3635–3370	Humerus
Kilgreany burial B	Waterford	Pta -2644	4820	60	3711–3379	Skull
Poulnabrone	Clare	OxA-1906	5100	80	4052–3696	Right talus
Poulnabrone	Clare	OxA-1910	4940	80	3951–3538	Right talus
Poulnabrone	Clare	OxA-1905	4930	80	3947–3536	Right talus
Poulnabrone	Clare	OxA-1912	4810	80	3766–3376	Right talus
Poulnabrone	Clare	OxA-1911	4720	70	3636–3377	Right talus
Poulnabrone	Clare	OxA-1909	4550	80	3627–3029	Right talus
Poulnabrone	Clare	OxA-1907	4520	80	3501–3026	Right talus
Sramore Cave	Leitrim	UB-6407	5202	39	4217–3967	Right femur
Stoneyisland	Galway	OxA-2942	5270	80	4326–3957	Unspecified
Stoneyisland	Galway	OxA-2943	5180	80	4232–3796	Unspecified
Stoneyisland	Galway	OxA-2941	5170	90	4237–3370	Unspecified

with previous dates from these two sites (Lynch 1988; Hedges *et al*. 1990; Lynch and Ó Donnabháin 1994; Ó Floinn 2012; Schulting 2014), while the middle Neolithic date from Kilgreany is somewhat later than the dates previously obtained there (Dowd 2002; 2008; Hedges *et al*. 1997). Unfortunately, the tooth from Ballynaclogh was too collagen-depleted to provide a radiocarbon date or δ^{13}C and δ^{15}N isotope values.

Stable isotope results

Analysis of the eight successful collagen samples for δ^{13}C and δ^{15}N at the ^{14}CHRONO Centre provided an indication of the individuals' diets (Table 1; Fig. 3). With one exception, all of the individuals analysed have δ^{13}C of less than –20‰. This suggests an almost exclusively terrestrial C_3 source for dietary protein (Cadwallader *et al*. 2012). The one exception (PNB02) has a collagen δ^{13}C of −19.6‰. Although this is slightly more enriched than the other individuals from the site, it is still greatly depleted relative to the −15‰ expected for a marine protein source (Richards and Schulting 2006, 450). These figures compare well with what is generally seen in Neolithic Ireland and Britain (Schulting and Richards 2000), where it is believed that the diet consisted almost entirely of terrestrial sources and, more specifically, domesticated crops and animals. This, however, makes the two Mesolithic samples from Stoneyisland and Sramore Cave even more interesting. The fact that they are clearly in the terrestrial bracket highlights that the Irish Mesolithic diet was not necessarily heavily seafood-based. As both of these sets of remains are from inland locations, this seems to support Woodman's (2004) assertion that the Irish Mesolithic diet was largely dependent on location. But in turn this also makes us question the concept of a seasonal round between coastal areas and inland locations during the Irish later Mesolithic (Kador 2014; Woodman *et al*. 1999). If people spent part of each year by the coast subsisting primarily on marine resources, we should expect their δ^{13}C (and δ^{15}N) values to reflect this.

The δ^{15}N readings further support the largely terrestrial signature of all the individuals analysed. All the results are below the 12‰ generally considered a rough threshold between terrestrial and marine diets from inland locations (Post 2002, 703–4). The Mesolithic individual from Stoneyisland (STI01), however, with a δ^{15}N ratio of 11.82‰, has values that are markedly more enriched than those for any other sample. As the δ^{13}C is terrestrial, not marine, this result could suggest that this individual consumed a diet rich in freshwater fish, with higher trophic levels than terrestrial foods (Fuller *et al*. 2012; Kimball 2006; Meiklejohn and Woodman 2012). This is especially interesting as Stoneyisland Bog is directly adjacent to the northern shore of Lough Derg, which forms part of the Shannon river system, and tallies well with recent discoveries of later Mesolithic fish-traps in Ireland (Fitzgerald 2007; McQuade and O'Donnell 2007) and the focus on freshwater fish associated with Mesolithic settlement in the Irish midlands (Fredengren 2002; Little 2009; O'Sullivan 1998).

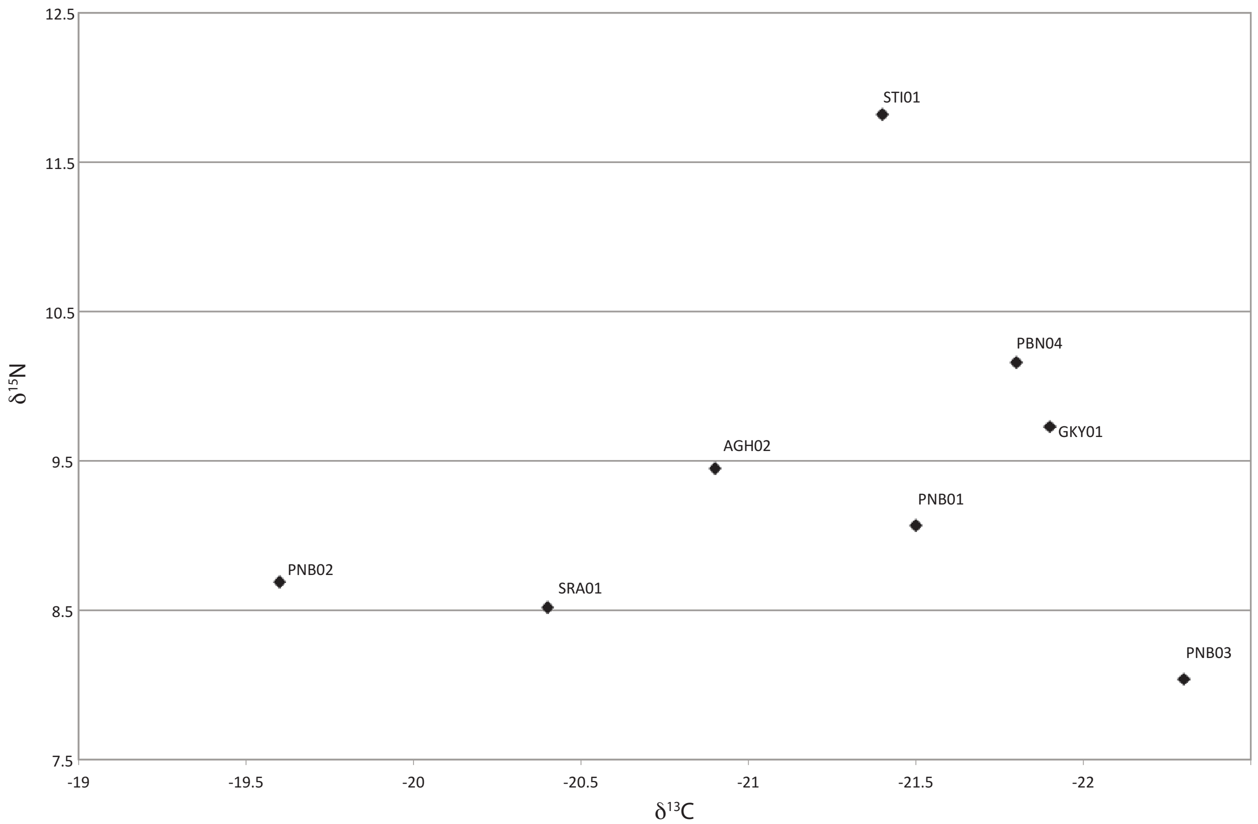

Fig. 3—δ^{13}C and δ^{15}N results.

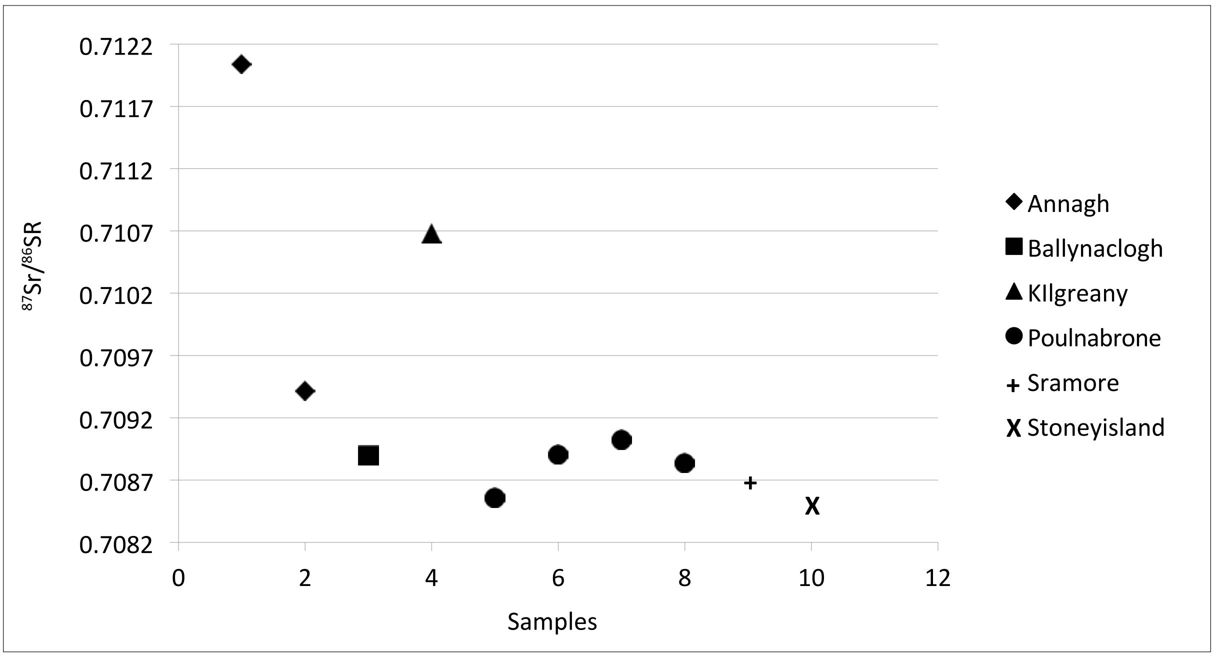

Fig. 4—^{87}Sr/^{86}Sr results.

Although the sample size is too small to draw any meaningful conclusions, the $\delta^{15}N$ results from Poulnabrone are also interesting. The $\delta^{15}N$ ratios from PNB02 and PNB03, representing a probable and a possible adult male, are considerably lower than those from PBN01, which represents a probable adult female, and PNB04, which belongs to a juvenile. It is possible that the elevated trophic levels in the juvenile could represent an example of a weaning signal resulting from breast-feeding (Mays *et al*. 2002). In relation to the difference in values between PNB02 and 03 on the one hand and PNB01 on the other, it would be interesting, based on a larger sample size, to explore further whether there could be a difference in diet between Irish Neolithic males and females.

Strontium isotope analysis

The results from the strontium analysis returned an $^{87}Sr/^{86}Sr$ range from 0.7084 to 0.7120 (Table 1), which encompasses a large proportion of Ireland's bedrock geology (Dempsey *et al*. 1990; Evans *et al*. 2010; Meighan *et al*. 1988; Mohr 1990; O'Connor 1988). Ireland currently still represents a relatively blank canvas in terms of bio-archaeological strontium isotope data. Consequently, there are few samples available against which these results can be compared, making detailed interpretation regarding the local strontium range in any particular region very difficult. As we acquire a more in-depth understanding of the local strontium ranges across the Irish landscape, this detail will become more readily apparent and will allow for more nuanced interpretations. While for the moment the strontium ratios had to be interpreted based primarily on the general geological regions from which the samples were recovered and by comparison to the strontium map for Britain of Evans *et al*. (2010), we have also analysed a limited number of background samples derived from vegetation from some of the sites discussed here (Table 2). As we have outlined above, directly relating the strontium ratios from human and animal teeth to bedrock geology is extremely problematic and can only be done to provide very basic indications, primarily to discern whether it is likely that an individual appears to have been local to the region where he/she was buried. Therefore even the very limited number of vegetation samples provided here can aid this process of elimination greatly.

In theory, all the ratios from the ten individuals could be argued to lie within the local range for the six find locations (Fig. 4). Some of the individuals' $^{87}Sr/^{86}Sr$ ratio seems to differ, however, from what might be expected. For example, PNB01, the only possible adult female analysed from Poulnabrone, has a lower $^{87}Sr/^{86}Sr$ ratio than the other three Poulnabrone samples. This difference is very small, however; moreover, all the values from Poulnabrone are in line with thirteen samples from the same site recently analysed by Ditchfield (2014), with an average $^{87}Sr/^{86}Sr$ ratio of 0.7087.

Potentially more interesting is the fact that the two individuals from Annagh Cave (AGH01 and AGH02) whose ^{14}C dates place them chronologically close together (Table 1) have entirely different Sr ratios. As all of the (five) individuals excavated at Annagh have been identified as probable males (Ó Donnabháin 2012), this differentiation in movement patterns clearly does not relate to a sex-specific difference. The $^{87}Sr/^{86}Sr$ ratio of 0.70942 from AGH02 tallies well with the result from the locally sampled vegetation sample (of 0.70952). It also corresponds well with what would be expected for the Carboniferous limestone surrounding Annagh Cave. For example, the average value for human dentine samples from Carboniferous limestone in Britain, published by Evans *et al*. (2010, 3), is 0.7094. In contrast to this, AGH01 seems to have originated from an area of older geology, resulting in a more radiogenic strontium ratio. In fact, with an $^{87}Sr/^{86}Sr$ ratio of 0.71204, AGH01 has a strikingly more radiogenic Sr signature than any of the other samples analysed as part of this study, which, as far as strontium isotopes are concerned, makes it potentially the most interesting of the samples analysed here. This does not necessarily mean that this individual came from a very long distance away, as there are regions of older geology (of Devonian Sandstone and Shale) in Ireland's mid-west region (Fig. 1). Whether these might give such a radiogenic strontium signature would need to be tested, however, through further analysis of the local biosphere strontium ratios in the region. Research on the Mourne Mountain granites has produced $^{87}Sr/^{86}Sr$ ratios between 0.710 and 0.713 (Meighan *et al*. 1988). Looking for broader comparisons, an $^{87}Sr/^{86}Sr$ ratio of 0.712 corresponds well with values on Ordovician and Devonian rocks in north Wales and Cornwall respectively (Evans *et al*. 2010).

STI01, with a value of 0.70849, provided the lowest $^{87}Sr/^{86}Sr$ ratio in this study. This could represent the lower range of values from Carboniferous limestones in Ireland (Ditchfield 2014; Douthit *et al*. 1993; Knudson *et al*. 2012). For example, Douthit *et al*. (1993) have reported $^{87}Sr/^{86}Sr$ ratios as low as 0.707650 from a long (429m) core of Irish Waulsortian Limestone from Prosperous, Co. Kildare, albeit at a depth of 50.9m. By comparison to the dataset of Evans *et al*. (2010) it would seem more likely for a ratio of 0.70849 from human tooth enamel to point to a younger (e.g. Tertiary or Cretaceous) geology. The only region in Ireland of such geology is located in the north-east. For example, O'Connor (1988) has found that a Tertiary rhyolite from Tardee, Co. Antrim, produced an $^{87}Sr/^{86}Sr$ ratio of 0.7085. Furthermore, the vegetation samples collected at Stoneyisland returned a ratio of 0.70894, considerably more radiogenic than that of the human remains and more in line with what could generally be expected for a Carboniferous limestone region. Two possible explanations for the ratio from Stoneyisland are, first, that this person spent his/her early years in an area of Tertiary geology such as north-east Ireland, or, second, that this Sr ratio resulted from a mixing of distinct geological sources owing to a highly mobile lifestyle during the individual's childhood. Similarly, the ratio from SRA01 (0.70863) appears relatively low for its location in north-west Ireland. While accepting the possibility of a low $^{87}Sr/^{86}Sr$ ratio from limestone (Douthit *et al*. 1993), this may also point to a younger rock formation than can be found in the surrounding region of Sramore Cave. The vegetation samples from the vicinity of the cave (collected by TELLUS Border) produced an average $^{87}Sr/^{86}Sr$ ratio of 0.70898 but ranged from 0.70827 to 0.70936. It is thus not inconceivable that the individual could have been relatively local to the region.

Clearly, ten individuals from a variety of different contexts represent a limited sample from which to draw substantial conclusions or generalise about population movement in early prehistoric Ireland. Moreover, the limited room for interpretation highlights the need for a greater research focus on mapping and understanding the biologically available strontium ratios across the Irish landscape. Having said that, the strontium ratios from these ten samples demonstrate that there is considerable variation within this dataset and suggest that an expanded programme of strontium analysis could reveal interesting stories about human movements in Irish early prehistory. In particular, questions that should be explored relate to the relationship between variations in movement patterns according to sex and changes in mobility over time.

Conclusions

While the scope of this study is limited, comprising a relatively small sample of human remains from Ireland's earlier prehistory, its findings make a potentially significant contribution to prehistoric research in the country. Moreover, little is still known about the expected biosphere strontium isotope range for many parts of Ireland, and especially in the western half of the country. Consequently, the results presented here contribute not only to our understanding of movement, mobility and diet between the sixth and fourth millennia BC but also help us to advance the discussion on the role of isotope studies in Irish prehistory. Finally, it is important that the results of archaeological isotope research on Irish prehistoric remains are placed in the public domain, even though most of them—like the present study—are based on relatively small-scale datasets. Otherwise it is difficult to see how we can advance these discussions and demonstrate the need for greater, more concerted efforts and investment to produce the isotope background data required to make our interpretations of isotope analyses more meaningful.

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